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THE SELECTION OF AN APPROPRIATE WASTE MANAGEMENT SYSTEM FOR THE CITY OF ZABRZE USING MULTI-CRITERIA ANALYSIS

WYBÓR SYSTEMU GOSPODARKI ODPADAMI W OPARCIU O ANALIZĘ WIELOKRYTERIALNĄ NA PRZYKŁADZIE ZABRZA

Abstract

Finding solutions for regional waste management systems is task that requires difficult decisions. This paper presents and evaluates alternative solutions to this problem using the example of solution of this system by an example of the waste management in Zabrze. These strategies were assessed using measurable economic, environmental and social criteria. Subsequently, by using multi-criteria analysis for evaluating various aspects, the most favorable variant in terms of compromise was selected. This solution concerns the expansion of the existing waste sorting plant in the city through the addition of elements of mechanical-biological waste treatment. This option does not provide for the construction of installations for waste incineration.

Keywords: *waste management system*, *multi-criteria analysis*, *evaluation criteria*, *municipal waste*

Streszczenie

Znalezienie rozwiązania dla systemu gospodarki odpadami w regionie jest trudnym zadaniem decyzyjnym. W artykule przedstawiono wariantowe rozwiązania takiego systemu na przykładzie gospodarki odpadami w Zabrzu. Warianty te zostały ocenione poprzez mierzalne kryteria ekonomiczne, środowiskowe i społeczne. Następnie, uwzględniając wszystkie kryteria oceniające w różnych aspektach i wykorzystując analizę wielokryterialną, wybrano wariant najkorzystniejszy w sensie kompromisowym. Jest to rozwiązanie proponujące rozbudowę istniejącej sortowni w mieście o elementy mechaniczno-biologicznego przetwarzania odpadów oraz rozbudowę kompostowni pryzmowej. W wybranym wariancie nie przewidziano budowy instalacji do termicznego przekształcania odpadów.

Słowa kluczowe: *system gospodarki odpadami*, *analiza wielokryterialna*, *kryteria oceny*, *odpady komunalne*

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1. Introduction

The regional waste management system is a structure dealing with the collection, processing and final disposal of waste generated in a defined unit of settlement (municipality, district, voivodeship). Such a system must function correctly as far as technology is concerned and provide, according to the law, the processing of the waste stream emerging from the region. Due to the significant number of available waste processing technologies, it is possible to create various configurations of the system in the same region. The criterion for selecting the system can be based on economic or a social factors which determine the acceptability of implementing the chosen strategies. Additionally, environmental factors must be taken into account in the choice of the technology or system, i.e. the potential impact of the waste management system on the local environment. This comprehensive look at the waste management strategy means that the system becomes not only a structure of interconnected technologies, it also becomes a multi-level system taking into account environmental, economic, legal and social factors. Often, additional factors including the specifics of the region also require consideration [3, 4, 9–11, 14].

This paper presents an attempt to select, with the use of multi-criteria analysis, the best strategy for waste management in Zabrze, taking into account the economic, environmental and social criteria.

2. Waste management in Zabrze

The city of Zabrze is situated in the south - west of Poland, in the western part of Silesia. It is a one of the largest cities in the Upper Silesian Agglomeration, located in the western part of the Upper Silesian Industrial Region (50.18ºN, 18.46ºE). It occupies an area of 8047 ha (80.5 km^2). According to the data from the city council, the city had 176,140 inhabitants as of 30 June 2010. In 1991, the largest population in Zabrze was recorded – 205,789 people, which signifies a negative natural population growth. It is among the top five most populated cities in the Silesian voievodeship and belongs to the Upper Silesian Metropolitan Union [11–13, 14].

As with scg most cities of the Upper Silesia, Zabrze was characterized by heavy industry for many years. This provided the basis for the economic development of the city and determined the direction of its development. In recent years, a process of profound and rapid transformation has been observed. Currently, the mining in the vicinity of the city of Zabrze is carried out by:

– Kompania Węglowa S.A. Department KWK ‘Sośnica – Makoszowy’,
– Kompania Węglowa S.A. Department KWK ‘Bielszowice’,
– ‘Siltech’ Spółka z o.o. – in the vicinity of mine shafts of the former ‘Pstrowski’ mine.

After the restructurisation changes, the liquidation of large industrial plants, still the largest share in industry in the city is taken by coal mining, energy and coke industry. There is also an iron and steel foundry, metal production and metal product manufacturing. Additional industries include renovation, construction, agriculture and food manufacturing – these operate to a lesser extent.

Despite the industrial nature of the city and the region – about 50% (4016 ha) of the city areas is covered by forests, woodland, agricultural and recreational areas of which agricultural lands (arable land, meadows, pastures) in the city of Zabrze occupy 2343 ha [11, 14].

3. Waste management strategies

Waste management in the municipality of Zabrze is conducted on the basis of the 'Regulations for the Maintenance of Cleanliness and Order' (city council resolution no. LVI/702/06 of 3 July 2006). The system of waste management functioning in Zabrze consists of:
- mixed waste collection,
- segregation of recyclable materials 'at source',
- waste disposal in the segregation and composting plant,
- landfill at the municipal waste landfill in Zabrze, at Cmentarna Str. #19; the landfill is the property of the municipality of Zabrze.

Mixed waste is collected in the container system. Recyclable materials are collected selectively, and include: waste paper, glass, plastic and kitchen waste (from volunteers). Received recyclable materials go to the segregation and composting plant in Zabrze. After segregation, they are transported to the recovery and recycling facilities located outside the boundaries of the municipality of Zabrze. The plan assumed mixing this waste with green waste in the composting plant and its oxygen processing and use compost for land rehabilitation. However, due to their significant contribution to pollution, only green waste is currently composted. Green waste for composting comes mainly from urban areas, whereas from private owners, it is collected on request.

In addition, collections of drugs and batteries are organized in the municipality – these are passed on to special customers. Similarly, bulky waste is collected. In designated areas in the municipality, there are waste containers provided for this waste. The dates and locations are announced in local newspapers and on official websites. In October 2008 in the segregation and composting plant, a waste collection point for electrical and electronic equipment waste from private households was also established.

Currently, the Segregation and Composting Plant has the following capacity:
- sorting plant – 4000 Mg/year of separately collected recyclables at two shifts work,
- composting plant with prism installations with a capacity of 5 000 Mg/year.

Considering the data from waste transporters, waste accumulation rates in Zabrze were 268.3 kg/M/year for 2007, whereas for 2008, the figure was 265.5 kg/M/year (with the rate for the whole country being 275 kg/M/year, and for Śląskie Voivodeship – 250 kg/M/year, as defined by NWMP in 2010 and PWMP). The average composition of waste in the analysed region is shown in Table 1.

The analysis of the existing allowed considering three variants for the waste management system for the city of Zabrze.

Variant I proposes the following features:
- The incineration plant for the unsorted waste, with a capacity of 60,000 Mg per year, located in areas adjacent to the segregation and composting plant in Zabrze on the premises belonging to the power plant;

– The increase of processing volume of the sorting plant of waste coming from selective waste collection of 15,000 Mg per year including bulky waste processing, accepting hazardous waste, and construction waste processing;
– The existing composting plant with the addition of composting plant for green waste and kitchen waste with the current capacity of 5,000 Mg per year;
– Storage of waste residue in a landfill in Zabrze.

Table 1

The average morphological composition of municipal waste for the Silesia Voivodeship [11, 12]

Fraction of waste [%]	Urban	Rural	Infrastructure
Biodegradable kitchen waste	33	18	10
Green waste	2	4	2
Paper and paperboard	20	12	27
Multi-material waste	4	3	18
Plastics	14	12	18
Glass	8	8	10
Metal	5	5	5
Clothing, textiles	1	1	3
Wood	2	2	1
Hazardous waste	1	1	1
Mineral wastes	10	34	5

Variant II proposes the following features:

– The increase of processing volume of the sorting plant with the elements of the mechanical-biological treatment of waste, as the so-called waste management plant. The plant will accept mixed municipal waste in quantities of 55,000 Mg per year and segregated waste for final purification in the amount of 15,000 Mg per year. As the result of processing a stream of waste, mineral fraction will be obtained for storage, secondary raw materials for further use, refused derived fuel directed to a cement plant and the organic fraction, which will be mixed for composting with green waste; on-site bulky waste processing is provided, as well as hazardous waste reception and processing of construction waste;
– The increase of processing volume of the composting plant with prism installations up to a capacity of 10,000 Mg per year for the following waste: green waste, kitchen waste and biological fraction separated from mixed municipal waste;
– The incineration plant is not planned in the region;
– Storage of waste residue in a landfill in Zabrze, Cmentarna Str.

Variant III proposes the following features:

– The increase of processing volume of the sorting plant with elements of mechanical--biological treatment of waste, as the so-called waste treatment plant; the facility will accept mixed municipal waste and recyclable materials as in Variant II. Processing of the

waste stream will result in obtaining mineral fraction to be stored, recyclable materials to be used and residual waste to be sent to the thermal conversion; the plant will also process bulky waste, accept hazardous waste, and construction waste,
- The existing composting plant with prism installations for green waste and kitchen waste with the current capacity of 5,000 Mg per year;
- Incinaration plant with a capacity of 40,000 Mg per year of waste recovered from the plant; a key node of the associated system of the comprehensive waste treatment for the city of Zabrze will be the installation for thermochemical transformation of the total organic matter from various waste into standardized average-calorific industrial gas containing mainly hydrogen and carbon monoxide, and a composition allowing its use in the energy processes and in chemical production; in order to simplify the whole system in Variant III it is assumed that the whole stream of mixed municipal waste will go directly to the incineration plant equipped with appliances for pre-enrichment of organic matter through the sifting of mineral fraction and by drying up with the waste heat. The installation will be located in areas adjacent to the currently existing Segregation and Composting Plant in Zabrze on the premises belonging to the Power Plant;
- Storage of waste residue in a landfill in Zabrze, Cmentarna Str.

4. The criteria for evaluating the operation of the waste management system

To assess the variants of the waste management system in Zabrze, the criteria were proposed for evaluation in the following groups:
- Economic criteria – evaluating the economic aspects of the system variants, their costs and capital expenditures; these are usually the criteria considered by policymakers as the most essential in the evaluation of investments in environmental engineering;
- Environmental criteria – defining the influence of individual variants of the waste management system on the environment through the assessment of the volume of emissions to the environment as a result of the operation of individual installations of the system;
- Social criteria - defining the degree of public acceptance of variants of waste management in Zabrze; usually the criteria which are most difficult to measure and therefore often not taken into account in the design of investment in environmental engineering.

Economic Criteria

The net present value (NPV) of an investment project associated with the implementation of the variants was, at the time of the anticipated start of its implementation (2008), determined by discounting the cash flow (CF) during the whole life of the operation of elements of this variant (for each year separately and at a certain constant discount rate r = 5%). The list of evaluation criteria for the variants is presented in Table 2, in the group of economic criteria. By analyzing their values, it must be remembered that in Variant I, income is achieved only in the last years of the adopted 15-year end of the investment project implementation. Due to the above, Variant I should be regarded as the least cost-effective option (negative NPV). Variant II turns out to be the best in this category as it generates the lowest costs for treating one ton of waste and has the lowest capital investment.

Environmental criteria

In order to determine the environmental criteria, which evaluate variants of waste management in Zabrze the LCA analysis stage, was used, constituting the inventory of the inputs and outputs to the system. For the assessment, the CML 2001 method was chosen taking into account the EU Directive 2001/42/EC on Strategic Environmental Assessment. In order to reflect the full spectrum of the negative impact on the environment, the following environmental effects were analysed [14]:

– abiotic depletion indicator – AbDe, related to the parameters of antimony deposits, measured in [kg Sb_{eq}/year];
– climate change indicator – ClCh, measured in [kg CO_{2eq}/year];
– human toxicity indicator – HuTo [kg 1.4 dichlorobenzene $_{eq}$/year];
– photo-oxidant formation indicator – POFo, measured in [kg ethylene $_{eq}$/year];
– acidification indicator – acid, measured in [kg SO_{2eq}/year];
– eutrophication indicator – eutr, measured in [kg PO_4^{3-}/year].

The list of evaluation criteria for the variants is presented in Table 2, in the group of environmental criteria. The comparison of such a number of criteria creates certain difficulties in their interpretation, although in general it is clear that the best environmental results are obtained by a combination of energy recovery from the incineration plant with the recycling of fractions, which can be separated from the waste volume using relatively non-complex and energy-consuming process.

In addition, the environmental assessment takes into account energy consumption – this is presented in Table 2 as three additional criteria.

Social criteria

As the most difficult to evaluate, social criteria were described and measured on a point-based grading scale by an expert method. The variants are assessed on a scale of 1–3 (where 1 signifies the best value, and 3 indicates the worst). The combination of these criteria are also presented in Table 2 in the group of social criteria with division into 3 subgroups: social – evaluating social acceptance for the different variants; social – taking account of social justice in the implementation of various variants; social – considering social functionality.

5. Multi-criteria analysis and the selection of the best strategy

Using the criteria for assessing the waste management system for Zabrze [11, 12] (Chapter 4) and the developed variants of the system presented in Chapter 3, the analysis and selection of the best possible system was performed. The selection was based on a multi-criteria analysis, which is a mathematical method. The condition for finding a solution is the adoption of a set of criteria (indicators) evaluating specific variants [1, 2, 5–8]. In order to objectively and extensively assess the task, it is best that the criteria include various aspects of the evaluated variant, although they may present different, often conflicting goals. The mathematical record of the mathematical decision-making problem is the so-called decision-making matrix. This is a matrix that recognises the description of the specific variants with the criteria that describe these variants. The criteria recorded as a number from the matrix constitute the measure of the implementation of the adopted tasks and objectives that should be met by specific variants. The record of the decision-making matrix is shown in Table 2. For the purposes of calculation, the variants are named W1, W2 and W3.

Table 2

Decision-making matrix for the selection of a waste management variant in Zabrze [14]

Groups of criteria	Criteria/units	Variant I	Variant II	Variant III
		W1	W2	W3
Economic	Capital expenditure [thousand PLN]	93,222.34	50,441.53	61,234.90
	Average annual operating costs [thousand PLN]	11,970.31	7,440.08	10,041.63
	Average annual income [thousand PLN]	19,364.63	15,242.52	21,444.92
	The net present value – NPV [thousands PLN]	–33,838.18	8,414.94	21,743.95
	Ratio of net present value – NPVR	–0.36	0.17	0.35
	IRR	–9.00%	8.00%	8.50%
	Profit or loss from disposal of one ton of waste – [PLN/ton in the 15th year of the investment]	–22.5	–1.17	–4.44
Environmental	AbDe [kg Sb_{eq}/year]	–313,000.00	–96,200.00	–268,000.00
	ClCh [kg CO_{2eq}/year]	–1,950,000.00	–4,930,000.00	7,870,000.00
	HuTo [kg $C_6H_4Cl_{2\ eq}$/year]	–22,700,000.00	661,000.00	–1,320,000.00
	POFo [kg ethylene eq/year]	21,400.00	–8,230.00	–7,480.00
	Acid [kg SO_{2eq}/year]	3,690,000.00	–164,000.00	–109,000.00
	Eutr [kg PO_4^{3-}/kg]]	893,000.00	–5,340.00	–469.00
Energy consumption	Electricity consumption [MWh / year]	1,441.85	3,329.76	8,007.38
	LPG [l/year]	3,040.00	2,600.00	3,140.00
	Consumption of diesel oil [l / year]	254,230.00	41,824.00	57,384.00

Social – evaluating acceptance of the system	Odours	1	1	1
	Visual impact	1	1	1
	Comfort	1	1	1
	Urban space	1	1	1
	Private space	2	1	2
	Noise	1	1	1
	Complexity	1	1	1
	Traffic	1	2	2
	Risk perception	3	1	2
	Morbidity and mortality	1	1	1
	Changes in prices of land and real estate	1	1	1
	Deterioration of living conditions close to the investment	1	1	1
Social – considering social justice	Availability of the waste management system	1	1	1
	Quality of employment	1	1	1
Social – considering social functionality	Solutions to the problem of household waste	1	1	1
	Creating job positions.	3	2	1

To solve the decision task, the method of compromise programming was used. This allows classifying the variants from the most to the least favorable using the concept of sorting them according to their distance from the so-called ideal point with coordinates X' $(x'_1, x'_2, \ldots, x'_m)$. All the coordinates of the ideal point are equal to the maximum value of the adopted scale of standardisation, i.e. they always assume the best value. The mathematical record of the measure of the distance sought of the studied variant from the ideal point is:

$$L_\alpha(s_n) = \sum_{m=1}^{M} w_m^\alpha \cdot (x'_m - r'_{NM})^\alpha$$

However, the choice of the best strategy takes place according to the rule:

$$s_j = \bar{s} \Leftrightarrow L_\alpha(s_j) = \min L_\alpha(s_n); \quad n = 1, 2, \ldots, N$$

where:

$L_\alpha(s_n)$ – the measure of the divergence of a given strategy s_n from the ideal point,
$\overline{s}$ – the chosen strategy,
w_m – weight ratio of the criterion m,
x'_m – m-th coordinate of the ideal point,
r'_{NM} – normalised value of the criterion,
M – number of criteria,
α – an exponent measuring the deviation of a strategy from the ideal point X', assumed in practice as 1, 2, and ∞.

The method, in addition to taking into account the values of the criteria, provides the additional possibility of weighting the various criteria or groups of criteria, i.e. there exists the possibility of additional consideration in the calculation of the validity of some parameters that are of particular importance to the decision maker. For the objectivity of calculation in this publication, more weight was given to all groups of criteria in succession, which allowed tracing the results of the calculations and to carry out the sensitivity analysis of the obtained solutions, depending on the weights assigned. The results of calculations with the weights of each group of criteria are presented in Table 3.

Table 3

The ranking of variants of waste management systems based on the weighting of individual criteria groups

Weights of criteria groups: economic; environmental; energy consumption; social (acceptance); social (justice); social (functionality).	The ranking of variants of the waste management system for Zabrze		
	$\alpha = 1$	$\alpha = 2$	$\alpha = \infty$
1:1:1:1:1:1	W2*→W3→W1	W2*→W3→W1	W2*→W3*→W1
2:1:1:1:1:1	W2*→W3→W1	W3*→W2→W1	W3*
5:1:1:1:1:1	W3*→W2*→W1	W3*→W2→W1	lack of solution
1:2:1:1:1:1	W2*→W3→W1	W2*→W3*→W1	lack of solution
1:5:1:1:1:1	W2*→W3→W1	W3*→W2*→W1	lack of solution
1:1:2:1:1:1	W2*→W3→W1	W2*→W3→W1	W2*
1:1:5:1:1:1	W2*→W3→W1	W2*→W1→W3	lack of solution
1:1:1:2:1:1	W2*→W3→W1	W2*→W3→W1	W2*→W3
1:1:1:5:1:1	W2*→W3→W1	W2*→W3→W1	lack of solution
1:1:1:1:2:1	W2*→W3→W1	W2*→W3→W1	W2*→W3*→W1
1:1:1:1:5:1	W2*→W3→W1	W2*→W3→W1	W2*→W3*→W1

1:1:1:1:1:2	W2*→W3→W1	W2*→W3→W1	W3*→W2
1:1:1:1:1:5	W3*→W2*→W1	W3*→W2→W1	W3*→W2
5:5:1:1:1:1	W2*→W3*→W1	W3*→W2→W1	lack of solution
5:5:5:1:1:1	W2*→W3→W1	W2*→W3→W1	lack of solution
1:1:1:5:5:5	W2*→W3→W1	W2*→W3→W1	lack of solution
1:5:1:5:5:5	W2*→W3→W1	W2*→W3*→W1	lack of solution
5:1:5:1:1:1	W2*→W3→W1	W2*→W3→W1	lack of solution

* Acceptable variants

The table shows the ranking of variants from the most favourable to the least favourable, considering the evaluation criteria from Table 1. The ranking was noted using the mark '→'.

The first column of the table shows weights of the criteria adopted for calculations by the authors of the publication. For example, in the first line, technologies are ranked assuming the weight of all groups of criteria equal to 1, while in the next line, the first set of criteria – 'economic criteria' received weight 2, while all the others had a weight of 1. In the last lines, higher weights of criteria were assumed simultaneously for several criteria groups.

This method gives the possibility to additionally weight the criteria by using the exponent α in the formula. This exponent allows additionally weighting all deviations in proportion to their size, individually from the ideal point. The greater the value of α, the more significant are large deviations of the strategy from the ideal point. Individual cases of calculation taking into account different values of the α coefficient are presented in three different columns in Table 3.

Summing up the calculations, it can be said that:

– In 44 calculation cases, variant W2 was usually chosen (34 times) as the most favourable option; this variant assumes the expansion of the existing sorting plant with the elements of the mechanical-biological treatment of waste and the expansion of the composting plant with prism installations; however, it does not provide for the construction of a incineration plant;
– Variant W3 was chosen as more favourable if the economic criteria group was outweighed;
– The lack of a solution means that all strategies are infinitely far away from the adopted utopian point;
– As the most unfavorable variant, variant W1 was selected in each case – assuming the construction of a incineration plant for unsorted waste and the expansion of the existing waste sorting plant in Zabrze;
– In deciding to adopt one of the technological solutions, certain limitations can be adopted in the choice of variants, i.e. assume acceptable solutions which are close to the point of accepting the utopian point, not just one solution nearest to it. In these calculations, such limitations were assumed, i.e. the so-called acceptability threshold, calculated as:

$$s_n^* = 0.1 \cdot L_\alpha (s_n)_{\min}$$

In this article, such a limitation was used – the selected variants are indicated in Table 3 "*" – as acceptable variants. Most often they are variants W2 and W3.

Due to the fact that social criteria have been greatly fragmented and estimated only by an expert method, they were not included in the succeeding stage of the calculation. The results of calculations with the exclusion of the groups of social criteria are presented in Table 4.

Table 4

The ranking of variants of the waste management systems, depending on the weights of criteria groups, without taking into account social criteria groups

Weights of criteria groups: economic; environmental; energy consumption	The ranking of variants of the waste management system for Zabrze		
	$\alpha = 1$	$\alpha = 2$	$\alpha = \infty$
1:1:1	W2*→W3→W1	W2*→W3→W1	W2*→W3*→W1
2:1:1	W2*→W3*→W1	W3*→W2→W1	W3*
5:1:1	W3*→W2→W1	W3*→W2→W1	lack of solution
1:2:1	W2*→W3→W1	W2*→W3*→W1	lack of solution
1:5:1	W2*→W3→W1	W3*→W2*→W1	lack of solution
1:1:2	W2*→W3→W1	W2*→W3→W1	W2*
1:1:5	W2*→W3→W1	W2*→W1→W3	lack of solution
5:5:1	W3*→W2→W1	W3*→W2→W1	lack of solution
5:1:5	W2*→W3→W1	W2*→W3→W1	lack of solution
1:5:5	W2*→W3→W1	W2*→W3→W1	lack of solution

* Acceptable variants

Summarising the results of the calculations presented in Table 4, it can be said that:

– In 23 calculation cases, not including groups of social criteria, W2 was chosen as the most preferred variant (15 times) while W1 was in most cases chosen as the least favourable;
– Comparing the results in Tables 3 and 4, it can be stated that in this example, the social criteria do not affect the final result of the calculation and in both cases are identical;
– As in Table 3, limitations to adopt the acceptable variant were established, i.e. the so-called solution acceptability threshold, and the acceptable variants of the waste management system in Zabrze in Table 4 were marked with "*".

6. Conclusions

– The waste management system is a complex and complicated structure, the shape and form of which is dependent on the technical, economic, environmental and social criteria; finding the best solution for such a system is a difficult and multifaceted decision-making task;
– The most difficult task in the assessment of the system is to find evaluation criteria, which in the fullest will describe the decision task; in this example, the criteria for assessing the functioning of the system variants included: economic, environmental, and social criteria;

– To find the solution, a multi-criteria analysis was used, taking into account in the calculation all the calculated evaluation criteria; the analysis made it possible to find a compromise solution and to choose the most advantageous variant of the waste management system in Zabrze;
– The solution proposing the expansion of the existing sorting plant with elements of the mechanical-biological treatment of waste and the expansion of the composting plant with prism installations without an incineration plant was chosen as the best solution to the waste management system in Zabrze.

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